Tangential Discontinuities at High Heliographic Latitudes (--80°)

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Abstract. In this study, tangential discontinuities (TDs) near -80° heliographic latitude have been studied. Based on our quantitative definitions, we find that the TDs may generally be divided into two clear types. There is a distinct population of TDs small (< 40°) directional changes, About 19% of all high-latitude TDs are in this category. These types of TDs are. found at the edges of mirror mode structures. The latter are presumed to be locally generated by ion anisotropies, based on examination of the mirror mode instability criteria, Another 50% of high latitude TDs are associated with large field directional changes (> 600). These TDs typically are found at the boundary between two streams. The discontinuities have large normals in the plane perpendicular to the background field, as might be expected for features generated by currents flowing along the field. These discontinuities usually have larger current intensities than those of the mirror-mode related TI)s. The remainder of the discontinuities have angular changes which lie in between the mirror-mode-associated and the current-sheet-associated TDs.

Introduction

10 a recent study, *Tsurutani et al.* [1 994] have shown that there are many directional discontinuities (DDs) at high latitudes detected by Ulysses. In this previous study, these discontinuities were not separated into discontinuity type (tangential and rotational discontinuities). While rotational discontinuities (RDs) are sharp changes in the magnetic field direction and are believed to often be the phase-steepen; edges of Alfven waves, tangential discontinuities (TDs) are often thought of as structures separating totally different plasma regions [See Figure 25 in *Tsurutani et* al., 1996].

Previous studies of tangential discontinuities have all been based on data taken at very low heliographic latitudes *[Smith, 1973; Neugebauer et al., 1984; Lepping and Behannon, 1986]*. Ulysses offers our first opportunity to examine TDs at truly middle and high heliographic latitudes. In this paper we will only focus on the highest latitude that Ulysses attained.

Because the high heliographic latitude regions are dominated by large amplitude Alfven waves *[Tsurutani et al., 1994; Smith et al., 1995]*, and these Alfven waves are often phase steepened *[Tsurutani et al., 1994], we* would expect a high rate of rotational discontinuities. Furthermore, at high latitudes, there are no large stream/stream interaction regions (or stream/stream interactions with large velocity gradients), due to the nearly constant solar wind speeds found there *[Phillips et al,,* 1994]. Also there are very few CMES (coronal mass ejections) detected at high latitudes [Gosling *et al.,* 1994]. The boundaries of these latter structures are assumed to be TDs. However, recent studies [*Neugebauer et al., 1995; McComas et al., 1995]* have shown that there are many small stream/stream interactions detected in the solar wind coming from the high latitude corona hole. These small stream/stream interactions may also lead to TDs. Thus, at present we do not know what to expect for TD occurrence rates at high heliographic latitudes.

In this study we will examine TD's occurrence rates, magnetic field structures and their plasma properties over the solar pole at the highest latitudes. When possible, we will also examine their possible generation mechanisms. This is the first study of TDs at truly high heliographic latitudes.

Criteria and Data

In previous studies, various criteria were used to identify directional discontinuities. In this study, we first use the *Tsurutani and Smith* [1 979] criteria applied to one minute average magnetic field data. These selection criteria are $|\Delta B|/|B| > 0.5$, and $|B| \geq 2\delta$, where δ is the value of the field variance on either side of the DD. To identify clear tangential discontinuities, we then use the *Smith* [1973] criteria applied to high resolution (ones econd) data: $B_n/B_L < 0.2$ and $\Delta|B|/B_L \geq 0.2$, where B_n is the normal component to the discontinuity determined by a minimum variance analysis, B_L is the larger field magnitude one either side of the discontinuity, and $\Delta|B|$ is the change of the field magnitude across the discontinuity. In this study we use the RTN coordinate system, where $\bar{R}$ *is* radial direction from the Sun, $\bar{T} = \bar{\Omega} \times \bar{R}/|\bar{\Omega} \times \bar{R}|$ ($\bar{\Omega}$ is the solar rotation axis), and $\bar{N}$ completes the right-hand system.

Using the above criteria, we have examined 15 days of magnetic field data observed by Ulysses at the highest heliographic latitudes of the south polar pass (- -800). The interval is from day 226 to day 240 of 1994. The radial distance of the spacecraft from the Sun is -2.4 AU. As stated above, we first use a computer code to identify all directional discontinuities in the one minute average data. Next, we perform minimum variance analyses using the highest time resolution data to determine the normal directions. Finally, the tangential discontinuities are identified by the criteria mentioned above. From the 15 days of magnetic field data, we identify 1486 DDs. Of these, 78 are TDs. Thus, the occurrence rate of TDs relative to DDs is 5.2%.

In this study, we only use ion data (proton and alpha particles) for the construction of plasma beta and anisotropy. Because electrons are usually quite isotropic, the main contribution of plasma pressure anisotropy comes from ions. The ion data are acquired through a three-dimensional measurement. The highest time resolution is four minutes [*Bame et al.*, 1992]. The data include the solar wind speed, V_{sw}, proton density, N_p, alpha density, Na, proton temperature, T_p and alpha temperature T_a. In order to study the plasma pressure anisotropy, the ion temperatures for both proton and alpha particles have been decomposed into parallel ($T_{//}$) and perpendicular ($T_\perp$) components with respect to the background field.

Results

From an analysis of TDs using high resolution field data in minimum variance coordinates, we find that TDs generally may be divided into two types based on their field structures. Figure 1 gives an example of one type. The TD occurs at 0643:30 UT of day 235. l'he top three panels are the magnetic field in the minimum variance (MV) coordinates (B_i, B_j, and B_k), where i, j, and k are the eigenvectors in the maximum, intermediate and minimum variance directions, respectively. The ratio between first two adjacent eigenvalues is required to be greater than 5 (to ensure accurate MV determinations). The two vertical

← Fig 1

dashed lines bound the region selected for MV analysis. l'he interval of analysis was chosen such that the full field magnitude change was detected. 1 f the fields on either side of the discontinuity were free of waves, then an interval slightly larger than the discontinuity alone was used. The next three panels are the magnetic field components shown in a RTN spherical coordinate system. They are the magnetic field magnitude, the two angular components, δ, the polar angle from R-T plane, -and ϕ, the azimuth angle increasing anti-clockwise from R in the R-T plane. The next panels are the solar wind proton density, temperature, speed, and ion beta ($\beta = 8\pi P_{th} / B^2$, where the ion thermal pressure pth includes both proton and alpha particle pressures). We have also made a correction to the parallel pressure due to the difference of both beam speeds, even though this causes only a 1-2,70 increase of parallel pressure at high latitudes. The bottom panel is the value $R=(\beta_\perp / \beta_\parallel)/(1+1/\beta_\perp)$, which is a measure of ion temperature anisotropy for mirror mode instability (respective to the background field). If *R is > 1,* mirror mode growth will occur, and if it less than one, this mode is stable. A more accurate expression about this criterion may be found in the studies of *Barnes* [1966].

In Figure 1, the magnetic field change mainly takes place in the i (maximum variance) direction. However, we note that the B_i does not change its sign (no reversal in direction). The discontinuity normal mainly points to the minus N direction with a unit vector (0.59, -0.06, -0.80). Across this TD, the field increases significantly from 0.4 nT (B_1) to 1.3 nT. The discontinuity appears at one edge of a low field region. The field vector has a small angular change (- 34°) across this discontinuity.

In Figure 1, accompanying an increase in the magnetic field in the upstream side of the TD, the plasma density decreases and the temperature slightly decreases. Thus the proton beta suddenly becomes small from a large value (> 10). There is no obvious variation in the solar wind velocity in this interval. The mirror mode instability value R is near 1.0 (marginal for growth). Thus, this low field region has all the characteristics of a mirror mode wave (that is, high beta, small field angular change and marginal instability). The B_i value which decreases, but does not reverse sign is also consistent with a mirror mode structure. For mirror modes, field decreases and increases are expected with little change in angle [*Tsurutani et al., 1982]*. On the left side of the TD there is a -20 min. interval with $R >$ 1.0. There are corresponding field decreases throughout this region.

Figure 2 gives another type of TD observed at high heliographic latitudes. The TD is detected at 1946:20 UT, day 239. The Figure has the same format as Figure 1. However, in the minimum variance coordinate system, B_i has a large change from positive to negative values across the zero line. This corresponds to a large directional change (- 11 2°) for the magnetic field across the discontinuity. The field magnitude decreases from 1.6 nT to 1.0 nT. On sunward side, the field magnitude is larger, the proton density (0.38 cm^{-3}) and temperature (1.9×10^5 K) are lower, and solar wind speed (758 km/s) is smaller than those in the downstream side (0.48 cm^{-3}, 2.2×10^5 K, 779 km/s) respectively. This tangential discontinuity clearly separates two different plasma media. This is apparently an interface between two velocity streams. Around this TD the ion beta ← Fig. 2

is quite high (~ 4), but the mirror instability criterion is constantly low (R ~ 0.6).

Through a minimum variance analysis, we find that the discontinuity normal is mainly in the -T direction with a unit vector (0,38, -0.83, -0.42) in the RTN coordinate system. We have calculated the current intensity in the minimum variance coordinate system, From the determined discontinuity normal direction, we find that the discontinuity is convected past the spacecraft at 300 km/s. We next convert temporal changes in B_i and B_j into spatial gradients, and thence to currents in the i and j directions. We find that the. current sheet associated with the TD has a large intensity of 2.0×10^{-10} A/m^2 in the j direction. Because the j direction has a unit vector (-0.88, -0.17, -0.45) in the RTN coordinate system, the current is mainly directed in the -R direction in SH coordinates The background field is found to be near anti-radial directed (-0.79, -0.25, -0.56). Thus, the current has an angle of ~9° with this background magnetic field. Other TDs associated with strong current sheets have been examined arrd have been found to have similar features in orientations and intensities. These currents are probably related to the small stream and polar plume structures in the high latitude region. However, our structures have much smaller scale than those found by *McComas et al.* [1995].

From the above two examples, we note that one TD occurs at an edge of a mirror mode structure and the other at a current sheet. It is natural to first determine how often these two types of TDs occur in our database. We have drawn these two types of magnetic field profiles in Figure 3. For a mirror mode structure (Figure 3a) the magnetic field strength has an obvious decrease in the center, but without field directional changes. The plasma density and temperature usually show an increase (when plasma data are available). On both sides of the mirror mode structure, the field strength is basically the same. The TDs should appear at the steepest field gradients (on both edges). For a current sheet structure (Figure 3b), there is usually an obvious boundary which separates two different plasma regions. Across the boundary the magnetic field changes the direction. The plasma velocity, density and temperature can also have significant changes, In order to identify these two types of TDs, we will give quantitative definitions as follows. ← Fig 3

We first examine the gross-scale magnetic fields in the vicinity of the discontinuity to see if the discontinuity is related to mirror-mode structures. We define a mirror mode structure to have a symmetrical or quasi-symmetrical "large scale" field structure. On both sides of the magnetic depression, the field strength should be the same within 20%. Both of the magnetic angular components (δ, ϕ) will be defined to have changes of less than 30°, The magnetic. field troughs in the mirror mode structure will have a width less than 10 min. Secondly, we also examine all gross-scale plasma parameters to determine if the TD is a boundary separating two different plasma regions. Across the boundary, we search for the following features: 1) velocity changes > 15 km/s, 2) density and temperature changes > 15% and 3) magnetic field directional changes > 60" in any one of two magnetic angular components in less than 10 min. If all of these criteria are met, we will define this structure as a current sheet. As a reference, we also examine the ion beta and pressure anisotropy. From this examination we find that 54 of 78 TDs may be classified as the two groups. The remainder of the discontinuities have properties intermediate between the two groups.

We find that 15 TDs are associated with clear mirror-mode structures. These discontinuities often appear at the edges of the mirror-mock structures. Thus, these TDs occur typically in pairs with a few of minutes separation between them. The magnetic field B_l does not reverse the sign (that is, not cross the zero line) in the MV coordinate system consistent with the picture of "ballooning" for these magnetic/plasma structures [*Tsurutani et al.*, 1982]. We also find that most (- 70%) of these discontinuities are associated with or close to regions of large ion pressure anisotropies.

Another type of TD is the current-sheet-associated TD. 39 TDs in this study have clear current sheet associated properties. This type of discontinuity is most likely an interface between two streams, The TDs are usually associated with strong currents in the range from 8.5×10^{-11} to 3.5×10^{-10} A/m^2. This is an order of magnitude greater than the currents associated with TDs near mirror-modes. The currents are typically oriented along the radial direction from the Sun. They are associated with obvious solar wind velocity gradients. The maximum variance field component reverses sign across the discontinuities.

The remaining 24 TDs have field and plasma properties that are not as easily categorized, One possibility is that they are a mixture of both mirror-mode-associated and current-sheet-associated TDs or are of a totally different type. They do not have the field structure typical of the mirror-mode related events discussed above. They also do not reverse their field direction in B_l as the clear current-sheet TDs do. The detailed structure and the generation mechanism of these TDs remain to be investigated.

In Figures 4a and 4b we show the three types of TDs using their directional change distribution, We calculate the directional changes of magnetic field vectors across the TD ($\vec{B}_1$ and $\vec{B}_2$) using one min. resolution data. The directional change is given by $\theta = \cos^{-1} \vec{B}_1 \cdot \vec{B}_2 / |\vec{B}_1||\vec{B}_2|$. TDs have a wide range of angular distribution from 10° to 160°. The mirror-mode-associated TDs have small angular changes, while most current-sheet-associated TDs have large directional changes as shown in Figure 4a. The remaining TDs have directional changes in between the two. Thus, the three types of TDs are very well separated in angular change. In Figure 4b, the mirror-mode instability index R has a general decreasing trend with increasing angles. This shows that the defined mirror-mode structures are most likely generated by large temperature anisotropies. ← Fig. 4

Summary and Discussion

From 1486 directional discontinuities identified within the 15 days of magnetic field data, we find 78 tangential discontinuities. The TD occurrence rate is 5.2% relative to all discontinuities. These TDs may generally be divided into two clear groups: mirror-mode-associated TDs and current-sheet-associated TDs. There are also TDs with properties intermediate between these two types. Mirror mode-associated TDs have small directional change (< 40°) across the discontinuity. They usually appear in pairs, at edges of mirror mode structures, Mirror-mode-associated TDs comprise -19% of all TDs in the high heliographic latitude regions. The current-sheet-associated TDs have large directional changes (> 600), They are usually associated with velocity gradients and currents oriented in the radial direction. The third type of TDs have intermediate angular distribution (30° > θ > 10OO). They have some mixed features of the above two clear types of TDs.

When both plasma beta and the anisotropy are large (larger β requires less anisotropy), the mirror mode will go unstable. By examining ion beta and the ion anisotropy, we find that all 15 mirror-mode associated TDs are associated with large beta (> 4.0). Eight of them occur when the instability index *R is* greater than 1,0 and are associated with gradual (positive.) gradients of solar wind speeds. In contrast, we only find that 3 cases out of all 39 current sheet-related TDs are associated with *R >1.0.* There is a general trend for R to decrease with increasing directional changes across TDs. Thus we propose that these mirror-mode-associated events are locally created. For those mirror mode structures associated with small velocity gradients, it is possible that the mirror mode growth has decrease gradients that previously existed.

We find that the rate of obvious TDs to all DDs is 5.2%, very similar to that in the ecliptic plane (2.5 to 12.7%, Smith, 1973; Neugebauer et al., 1984; Lepping and Behannon, 1986). Clearly at high latitudes we do not have TDs associated with CMEs and HCS crossings. However, since the high latitude and low latitude TD percentages are similar, it would be very interesting to know what types of TDs occur in the ecliptic plane. We will study this in the near future.

Acknowledgments: The authors would like to thank Marcia Neugebauer for her comments and suggestions, The research conducted at the Jet Propulsion Laboratory, California Institute of Technology was performed under contract to the National Aeronautics and Space Administration.

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(Received: June 1, 1995; Revised: August 30, 1995; Accepted: September 2, 1995.)

Figure 1. An example of mirror mode-related 'I'D. There is small field directional change across the TD. The TD appears at the edge of a mirror mode structure which is generated due to pressure anisotropy.

Figure 2. A case of current sheet-reli]ted TD. The TD separates two different plasma media. A solar wind velocity gradient is responsible for the generation of this type of I'D.

Figure 3. Two types of magnetic structures which are associated with simple TDs. a) A mirror mode structure has two TDs in both sides of edges, while b) a current sheet-related TD separates two different plasma region.

Figure 4. **Three** types of TDs and their angular change distribution. a) The mirror mode-related TDs have small directional changes and b) high temperature anisotropies, while the current sheet-related TDs have large directional changes and low anisotropies.

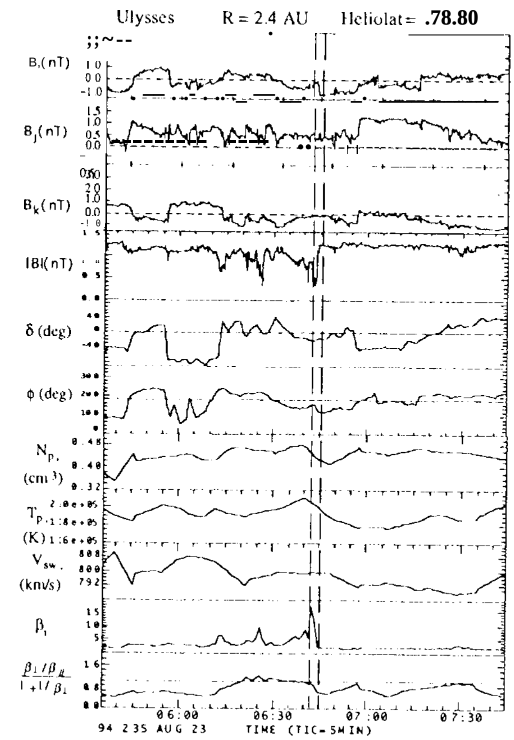
Ulysses R = 2.4 AU Heliolat= .78.80
B_i(nT)
B_j(nT)
B_k(nT)
|B|(nT)
δ (deg)
φ (deg)
N_p, (cm^{-3})
T_p, (K)
V_{sw}, (km/s)
β_i
$\beta_\perp/\beta_\parallel$
$1+1/\beta_\perp$
06:00
06:30
07:00
07:30
94 235 AUG 23 TIME (TIC=5MIN)

Fig 1

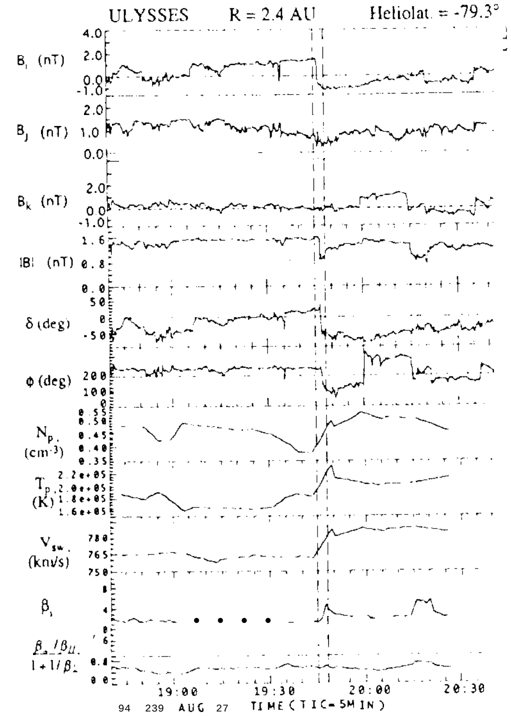
ULYSSES R = 2.4 AU Heliolat. = -79.3°
B_i (nT)
B_j (nT)
B_k (nT)
|B| (nT)
δ (deg)
φ (deg)
N_p (cm⁻³)
T_p (K)
V_sw (km/s)
β_i
β⊥/β∥ 1+1/β⊥
19:00
19:30
20:00
20:30
94 239 AUG 27 TIME (TIC=5MIN)

Fig. 2

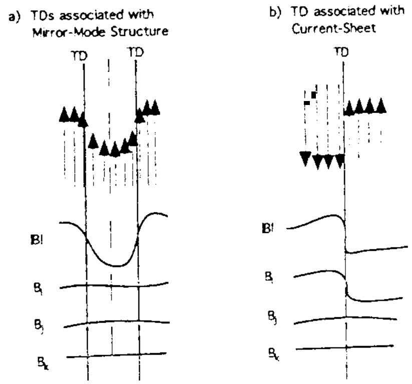
a) TDs associated with Mirror-Mode Structure
TD
TD
|B|
B_i
B_j
B_k
b) TD associated with Current-Sheet
TD
|B|
B_i
B_j
B_k

Figure 3

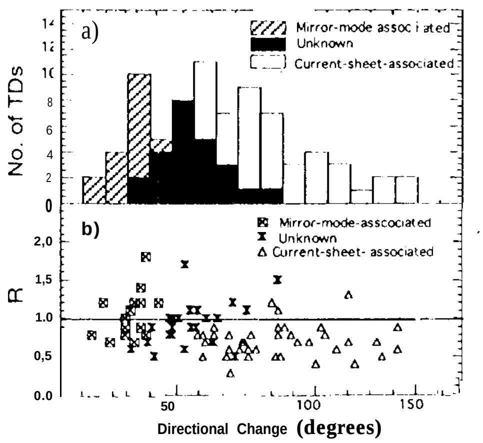
a)
Mirror-mode assoc i ated
Unknown
Current-sheet-associated
No. of TDs
b)
Mirror-mode-asscociated
Unknown
Current-sheet- associated
R
2,0
1,5
1.0
0,5
0.0
50
100
150
Directional Change (degrees)

Figure 4